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IONIZED ABSORBERS AS EVIDENCE FOR SUPERNOVA-DRIVEN COOLING OF THE LOWER GALACTIC CORONA

Filippo Fraternali[1,2], Antonino Marasco[1], Federico Marinacci[3,4], and James Binney[5]
[1] Department of Physics and Astronomy, University of Bologna, via Berti Pichat 6/2, I-40127 Bologna, Italy
[2] Kapteyn Astronomical Institute, Postbus 800, 9700 AV Groningen, The Netherlands; filippo.fraternali@unibo.it
[3] Heidelberger Institut für Theoretische Studien, Schloss-Wolfsbrunnenweg 35, D-69118 Heidelberg, Germany
[4] Zentrum für Astronomie der Universität Heidelberg, Astronomisches Recheninstitut, Mönchhofstr. 12-14, D-69120 Heidelberg, Germany
[5] Rudolf Peierls Centre for Theoretical Physics, Keble Road, OX1 3NP Oxford, UK
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ABSTRACT

We show that the ultraviolet absorption features, newly discovered in *Hubble Space Telescope* spectra, are consistent with being formed in a layer that extends a few kpc above the disk of the Milky Way. In this interface between the disk and the Galactic corona, high-metallicity gas ejected from the disk by supernova feedback can mix efficiently with the virial-temperature coronal material. The mixing process triggers the cooling of the lower corona down to temperatures encompassing the characteristic range of the observed absorption features, producing a net supernova-driven gas accretion onto the disk at a rate of a few $M_{\odot}\,\mathrm{yr}^{-1}$. We speculate that this mechanism explains how the hot mode of cosmological accretion feeds star formation in galactic disks.

Key words: galaxies: evolution – galaxies: ISM – galaxies: star formation – Galaxy: halo – ISM: clouds

Online-only material: color figures

1. INTRODUCTION

How the Milky Way and other disk galaxies acquire gas from their surrounding environment is a long-standing problem in galaxy evolution. Several pieces of evidence, for example, studies of the star formation in the solar neighborhood (e.g., Aumer & Binney 2009) and chemical evolution models (e.g., Chiappini et al. 1997), show that gas accretion is needed to maintain star formation. Since their discovery, high-velocity clouds (HVCs) have been regarded as the main source of neutral (H I) gas accretion in the Galaxy (e.g., Oort 1966). However, the recent determination of the distances to the main complexes (e.g., Wakker et al. 2008) has led to estimates of the accretion rate from HVCs that are at least an order of magnitude less than what is required (Putman et al. 2012). The same is true for HVCs found in external galaxies (Fraternali 2009). Mergers of gas-rich satellites also appear to fall short in providing the required amount of gas accretion (Sancisi et al. 2008).

During the last few years, the possibility that gas accretion manifests itself mostly as ionized gas has attracted a growing interest. Ultraviolet spectra against bright active galactic nuclei (AGNs) obtained with the Space Telescope Imaging Spectrograph (STIS) and the Cosmic Origins Spectrograph on board of the *Hubble Space Telescope* (*HST*) have revealed a number of ionized species at velocities incompatible with those of the Galactic disk material (e.g., Shull et al. 2009). The ions include C II, C III, C IV, Si II, Si III, and Si IV and cover a range of temperatures (assuming collisional ionization equilibrium, CIE) from a few times 10^4 K to 2×10^5 K. They fill about 70%–90% of the sky and they often have neutral gas associated with the absorption (Collins et al. 2009; Lehner et al. 2012). In a few cases they have been identified in the spectra of halo stars, showing that at least a subsample of them lies at distances within about 10 kpc of the Galactic plane (Lehner & Howk 2011) and ruling out formation in the distant corona or in the Local Group medium.

From a theoretical point of view, the accretion of fresh gas into galaxy disks is a non-trivial problem that has not yet reached a definitive solution. The scheme that has recently enjoyed most success is that of the so-called cold flows (e.g., Dekel & Birnboim 2006), where baryons reach the center of a potential well without going through a phase of virialization. Cosmological simulations suggest that cold flows are the main channel for gas accretion in the early Universe, but they should be replaced by a hot accretion mode for a galaxy like the Milky Way at $z \lesssim 1$ (e.g., Kereš et al. 2009). Thus, the problem of how to cool the hot gas contained in an extended virial-temperature corona and transfer it to the disk to feed star formation still remains. The formation of gas clumps in the corona via thermal instabilities has been explored (e.g., Kaufmann et al. 2006), but it has been ruled out both on theoretical (e.g., Binney et al. 2009; Hobbs et al. 2012) and observational (e.g., Pisano et al. 2007) grounds. Using hydrodynamical simulations, Marinacci et al. (2010) showed that gas at the typical temperature of the Galactic corona can cool efficiently if it is mixed with high-metallicity, cooler disk material. This mixing is enhanced by the onset of a galactic fountain circulation (e.g., Bregman 1980). Marasco et al. (2012, hereafter MFB12) used the fountain model of Fraternali & Binney (2008), together with the results of Marinacci et al.'s simulations, to reproduce the kinematics of the H I in the halo of the Milky Way. In this Letter, we show that the MFB12 model also explains the observational properties of the ionized absorbers detected by Lehner et al. (2012).

2. THE MODEL

We use the supernova-driven accretion model presented in MFB12, where cloud particles are ejected from the disk and move through the halo region interacting with the pre-existing Galactic corona. The details of this interaction are derived from the hydrodynamical simulations presented in Marinacci et al. (2010, 2011, the latter hereafter M11). In these simulations, a high-metallicity fountain cloud moves through a hot, low-metallicity plasma, representing the Galactic corona. Ram-pressure stripping and the onset of the Kelvin–Helmholtz instability produce a turbulent wake in which coronal gas is entrained and mixes efficiently with the disk material. The resulting medium at intermediate temperatures and metallicities,

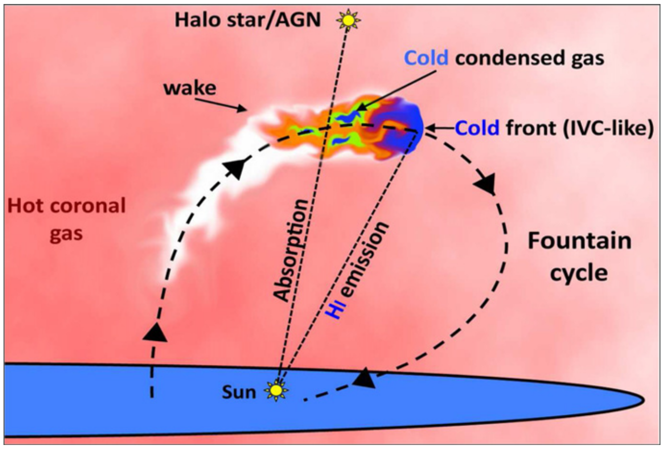

Figure 1. Fountain clouds, ejected form the disk by supernova feedback, travel through the halo and interact with the hot gas in the corona. The interaction creates a turbulent wake where coronal gas is entrained and mixed efficiently with high-metallicity disk material. This mixing produces a modification of the cold gas kinematics and triggers the cooling of some coronal material, which is then accreted onto the disk when the cloud falls back to it. An observer looking toward a background source intercepting the wake detects the absorption lines of the turbulent ionized material. An observer looking toward the cold front detects H I emission at velocities typical of intermediate-velocity clouds.

(A color version of this figure is available in the online journal.)

trailing the cloud front, can further cool down to recombination temperatures and produce a net transfer of mass from the hot coronal phase to the cold phase. This condensed coronal material is eventually transferred to the disk where it can feed star formation (see Figure 1). This mass transfer, together with a corresponding exchange of momentum, can significantly alter the clouds' trajectories, producing a detectable kinematic signature. MFB12 used this model to fit the kinematics of the Galactic H I halo in the Leiden/Argentine/Bonn (LAB) 21-cm Survey (Kalberla et al. 2005) and they determined that the mixing of disk and coronal gas triggers condensation and subsequent accretion of the latter at a rate of $\sim 2\,M_\odot\,\mathrm{yr}^{-1}$. Here, we use the same model to predict the properties of the material at intermediate temperatures in the wakes of the fountain clouds and compare them with those of the absorption features detected by Lehner et al. (2012). We do not perform a new fit but simply used the best-fit parameters that reproduced the kinematics of the H I halo.

From the simulations of M11 we selected only the gas in the temperature range $4.3 < \log(T/\mathrm{K}) < 5.3$. This range is representative for the species Si III, Si IV, C II, C III, and C IV assuming CIE (Sutherland & Dopita 1993). The gas selected with this temperature cut—hereafter the "warm" gas—is located in the wake of the cloud, typically within 2 kpc of the cold front. We studied the evolution of this warm gas with time, in particular its mass ratio and velocity difference with respect to the H I (assumed to be at $\log(T/\mathrm{K}) < 4.3$) and its velocity dispersion. We found that the warm gas lags 10–20 $\mathrm{km\,s^{-1}}$ behind the cold H I front and develops a turbulent motion with a velocity dispersion of $\sim 30\,\mathrm{km\,s^{-1}}$, which dominates over the thermal broadening. The details of this analysis are given in a parallel paper (Marasco et al. 2013). The dynamical model of MFB12 gives us the column density of neutral gas as a function of position in the sky and line-of-sight radial velocity. From this, using the above analysis, we can predict the column density of the warm gas at every location in the position–velocity space, which can then be compared with the *HST* absorption data. The photoionizing flux from the disk largely dominates the extragalactic contribution (Shull et al. 2009). Thus photoionization is probably non-negligible in the early stages of the clouds' trajectories: MFB12 found that the best fit to the H I data is obtained if the particles are ionized, and therefore are not visible in H I, for 30% of the ascending part of their trajectory. These ionized outflows are included in our model.

3. RESULTS

Figure 2 gives an all-sky view of the velocity field predicted by our model compared to the velocity centroids of the absorption lines detected by Lehner et al. (2012). Where there are multiple detections along a single line of sight, we have plotted the average velocity. Of the 84 absorption systems, 12 are considered to be related to the Magellanic Cloud/Stream and are not taken into account in our analysis. The top panel of Figure 2 shows the median velocity field predicted by the model, while in the bottom panel velocities are extracted randomly in cells of $2\overset{\circ}{.}5 \times 2\overset{\circ}{.}5$ to give a measure of the turbulent motions in the wakes. In both cases, we excluded warm gas at velocities $|v_{\mathrm{LOS}}| < 90\,\mathrm{km\,s^{-1}}$, as was done in the observations. The detections are not distributed isotropically in the sky: the targeted background sources are located mostly at positive latitudes, and no targets are present for $|b| < 15°$. Globally, the median velocity field predicts the correct dichotomy between detections at positive and negative velocities, indicating that the absorbing material is consistent with being part of a slowly rotating medium similar to that produced by the interaction between the galactic fountain and the corona (see also Fox et al. 2006; Shull et al. 2009). However, the data show large fluctuations around the predicted median value. The random velocity field (bottom panel) shows that fluctuations of similar amplitude are present also in our model. They are caused by the large velocity dispersion ($\sigma = 30\,\mathrm{km\,s^{-1}}$) of the warm material in the turbulent wakes of the fountain clouds.

Figure 3 shows the longitude–velocity distribution of the warm gas in our model in four different latitude bins. The absorption features of Lehner et al. (2012) are overplotted on these diagrams as filled and empty (if associated to the Magellanic Clouds/Stream) points. The contours enclose 68%, 95%, and 99.7% of the total flux present in the model, and are proportional to the probability of finding a detection at a given position and velocity if the background sources were isotropically distributed in the sky. Even though this is not the case, the absorbers follow a trend very similar to that predicted. We infer a fraction of detections that is consistent with our model by comparing the predicted and the observed distributions using a Kolmogorov–Smirnov test. The details are discussed in Marasco et al. (2013), where it is shown that the positions and velocities of $94^{+6}_{-3}\%$ of the UV absorbers are reproduced by our model. Thus, a large fraction of these ion absorbers are likely to be produced in the wakes of fountain clouds. These clouds would appear in H I as intermediate-velocity clouds (MFB12), but the ionized gas in the wake may have HVC-like velocities because it has a different kinematics and a much larger turbulence with respect to the H I. Interestingly, the fraction of ion absorbers reproduced by our model does not vary significantly if the detections that overlap with the classical H I HVCs are excluded from the calculation.

Shull et al. (2009) obtained an average column density for the high-velocity Si III absorption lines of $\langle \log N_{\mathrm{Si\,III}} \rangle = 13.42 \pm 0.21$, with velocity widths ranging from 40 to $100\,\mathrm{km\,s^{-1}}$. We compared this value with the prediction of our model by integrating line profiles of the warm gas over $70\,\mathrm{km\,s^{-1}}$ around

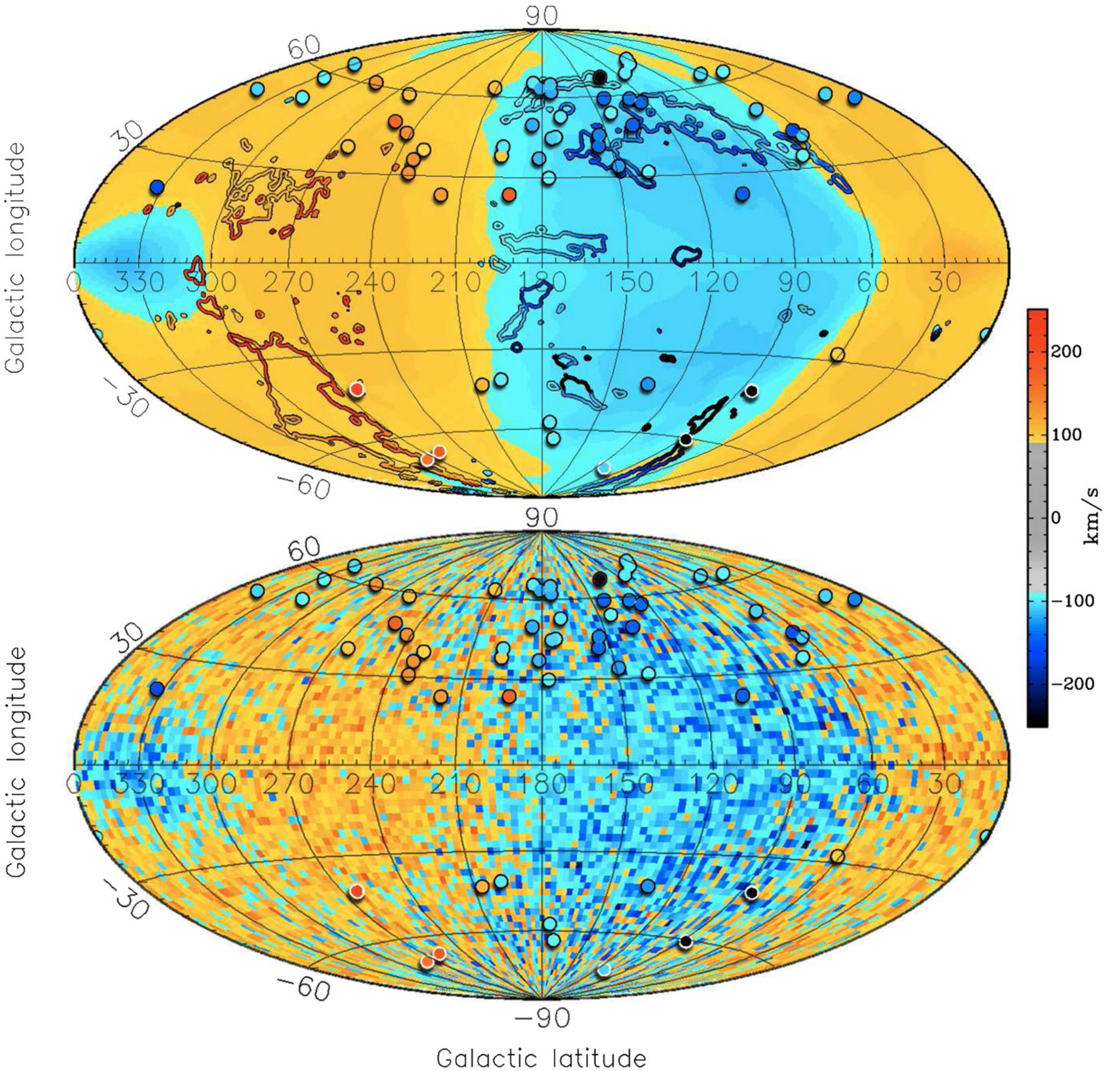

Figure 2. All-sky velocity maps comparing the absorption features detected by Lehner et al. (2012; circles) with the prediction of our model of supernova-driven cooling of the lower corona (background color). Multiple detections along the same line of sight are averaged in velocity so the number of points (65) in these panels does not correspond to the total number of detections (84). Circles with white borders represent absorptions that we consider to be associated with the Magellanic Clouds/Stream. The top panel shows the *median* velocity field, while the bottom panel shows velocities extracted randomly from our model in cells of $2.5^\circ \times 2.5^\circ$. The contours in the top panel show the H I emission from the classical HVCs and the Magellanic Stream, color-coded accordingly to their mean line-of-sight velocities.

(A color version of this figure is available in the online journal.)

the velocity centroid. To convert this value into an Si III column density, we further assumed solar abundance ratios and used the average metallicity of the warm gas in the simulations ($\log[Z/Z_\odot] = -0.24$) with the maximum Si III fraction in CIE (0.903 for $\log(T/K) = 4.45$; see Sutherland & Dopita 1993). We found an Si III column density, averaged over all the absorbers, of $\langle \log N_{\rm Si\,III} \rangle = 13.44 \pm 0.36$. Hence, the density of gas at intermediate temperatures produced in our model by mixing the fountain material with the hot Galactic corona is in remarkable agreement with the observations. Note that these column densities are derived assuming CIE, and this agreement may show that the gas is not too far from it. However, a doubling or tripling of the ion density by photoionization would be still compatible within the errors. We stress again that our model has not been fitted to the absorption data, the only fit that has been performed is on the H I component, which is related to the ionized material only by the cloud–corona interaction and the underlying physics of the turbulent mixing. Thus, this comparison strongly supports the validity of our approach.

A further comparison between our model and observations comes from counting the number of fountain-cloud wakes intercepted along the lines of sight. In our model, the Galactic

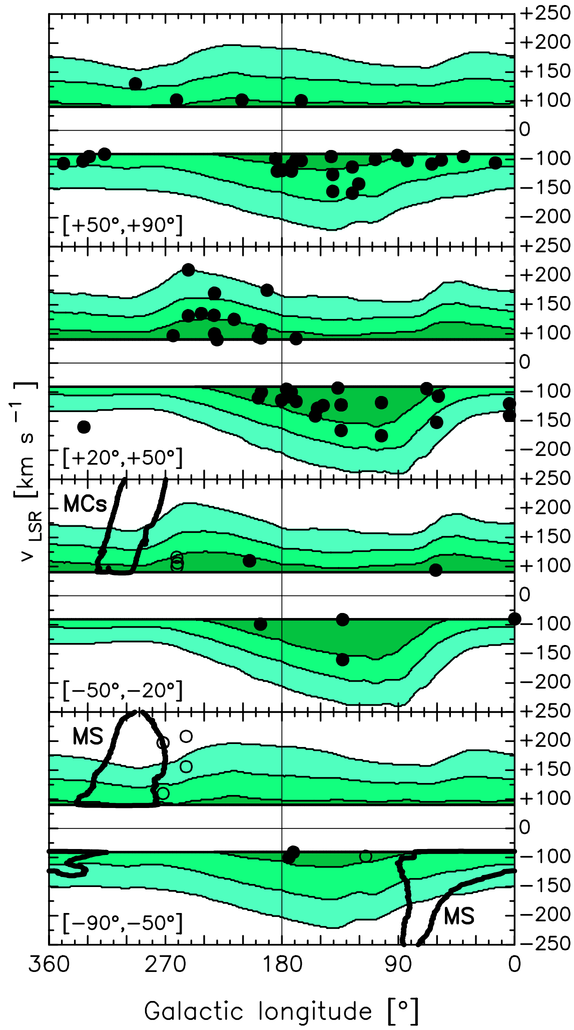

Figure 3. Longitude–velocity diagrams in four different latitude bins (bottom left corner) showing the confidence contours of our model of supernova-driven corona cooling. The circles show the location in longitude and velocity of the *HST* absorbers detected by Lehner et al. (2012). The empty circles are detections considered related to the Magellanic Clouds/Stream, whose H I emission is shown as the black thick contours. Five detections at very high velocities, four of which associated to the Magellanic Stream, are not shown in this plot.

(A color version of this figure is available in the online journal.)

halo is populated by $\sim 10^4$ fountain clouds, given the total H I halo mass ($\sim 3 \times 10^8\ M_\odot$; MFB12) and the mass of a typical (intermediate-velocity) cloud (few $\times 10^4\ M_\odot$; van Woerden et al. 2004). We considered that these 10^4 clouds are distributed around the Galactic plane with the density profile obtained by MFB12 for the H I halo. We assumed that each cloud has an associated wake, for which the volume occupied by the warm gas is derived from the M11 simulations. With the above information we estimated that an observer placed at the position of the Sun should intercept an average of 0.5–1.0 wakes per line of sight, which nicely compares with the average number of ~ 0.7 detections per line of sight in the data set of Lehner et al. (2012).

Sembach et al. (2003) and Savage et al. (2003) provide locations, velocities, and column densities for high-ionization (O VI) absorbers surrounding the Milky Way. Marasco et al. (2013) show that more than half of these absorbers are compatible with the same model of supernova-driven accretion presented here. Shull et al. (2009) provide velocity ranges for Si ions (Si II, Si III, Si IV) found in STIS and *Far-Ultraviolet Spectroscopic Explorer* spectra of 37 AGNs. We used the central velocities of these ranges and found that only 33.4% of these features are compatible with our model. This percentage becomes 63.2% when the data set of Shull et al. (2009) is considered together with that of Lehner et al. (2012). This result is surprising as it seems to show the two data sets are not fully compatible. It appears that most of the difference is due to a number of absorbers at high negative velocities in the region $20 < l < 120$ in the Shull et al. (2009) sample. Although this requires further investigation, it is possible that these absorbers lie in a large ionized envelope surrounding the Magellanic Stream (Bland-Hawthorn et al. 2007).

4. CONCLUSIONS

We have shown that the newly discovered UV absorption features in the Galactic halo, observed in *HST* spectra of bright AGNs and some halo stars, are largely consistent with the predictions of supernova-driven cooling of the Galactic corona. To make this comparison, we extended the supernova-driven accretion model of MFB12 by including the intermediate-temperature gas generated by the interaction between the galactic fountain clouds and the corona. We did not perform a new fit but used the best-fit parameters that match the H I kinematics in the LAB survey. Our model is able to reproduce the positions and velocities of the vast majority of the detected absorbers. Moreover, the model predicts the correct mean column density and the number of intervening absorbers along the line of sight.

Our findings support the idea that the vast majority of the absorbers are produced in a turbulent multi-phase layer a few kpc thick surrounding the Galactic plane. This layer is created by supernova feedback, which produces a galactic-fountain cycle that fosters the interaction between the high-metallicity disk material and the corona. The mixing of the two media lowers the temperature and increases the metallicity of the coronal gas, thus reducing dramatically its cooling time. As a consequence, part of the lower corona cools to lower and lower temperatures encompassing the range characteristic of the species considered in this work. When recombination occurs the gas is potentially visible in H I, but being buried within the fountain cycle it cannot be directly detected. This is the reason why cold gas accretion has escaped detection for so long. The only way to unveil its presence is via the effects that it has on the kinematics of the H I halo (Fraternali & Binney 2008; MFB12). This process produces a net accretion of fresh gas from the lower corona onto the disk at a rate of a few $M_\odot\ \mathrm{yr}^{-1}$.

In Figure 4 we compare the accretion rates onto the Galaxy that one can infer from the currently available gas sources. The classical HVCs contribute only $0.08\ M_\odot\ \mathrm{yr}^{-1}$, and only half of this gas is in the neutral phase (Putman et al. 2012). This value is uncertain and somewhat debated but still of the same order of magnitude as the previously often quoted value of 0.1–0.2 $M_\odot\ \mathrm{yr}^{-1}$ (Wakker et al. 2007). Direct accretion of cold gas from satellites is only visible in the Magellanic Stream, which is a sporadic event and it is very unlikely to reach the Galactic disk before being ablated and thermalized. If the Magellanic Stream survives the journey, it will merge with the Galactic Interstellar Medium (ISM) on a timescale likely larger than 1 Gyr (Putman et al. 2012). Given the H I mass of the Stream, $\sim 1.2 \times 10^8\ M_\odot$ (Brüns et al. 2005), this gives an upper limit to the accretion rate of $\sim 0.16\ M_\odot\ \mathrm{yr}^{-1}$. The galactic fountain instead produces an accretion of cold pristine gas onto the disk at a rate of $\sim 2\ M_\odot\ \mathrm{yr}^{-1}$ (MFB12). This value

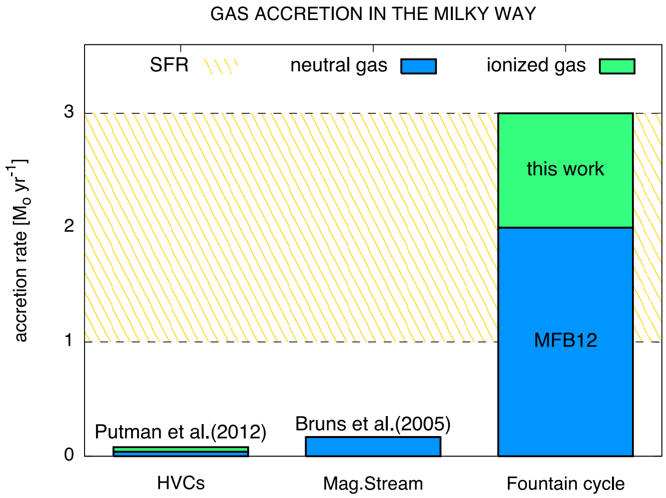

Figure 4. Comparison between different sources of gas accretion for the Milky Way. The estimate for the fountain cycle (supernova-driven accretion) comes from fitting the kinematics of the H I halo (MFB12) and it is confirmed by the ionized absorption features studied in this work.

(A color version of this figure is available in the online journal.)

is remarkably similar to the current star formation rate (SFR) of the Galaxy, which lies in the range 1–3 $M_\odot$ yr^{-1} (e.g., Diehl et al. 2006; Robitaille & Whitney 2010). In addition, from the present analysis, we infer a further accretion of $\sim$1 $M_\odot$ yr^{-1} of gas in the ionized phase, but it is unclear whether or not this gas can take part in the star formation process. Note that this value agrees with the estimates of both Lehner et al. (2012) and Shull et al. (2009). All the above estimates are corrected for He abundance. Clearly, the coronal material harvested by the fountain cycle provides the necessary gas supply for star formation to proceed.

Current cosmological simulations suggest that galaxies above a virial-mass threshold of a few times 10^{11} $M_\odot$ should acquire gas via hot-mode accretion, which mainly feeds the hot corona rather than the star formation in the disk. The galaxy's central black hole accretes gas at a rate that rises steeply with the corona's central density, and energy released by this accretion largely offsets the corona's radiative losses, which are dominated by its dense center (e.g., Omma & Binney 2004). The Milky Way and similar star-forming galaxies became massive enough to enter this regime of black hole stabilization at $z \gtrsim 1$ and consequently, in simulations, their SFRs have declined since then by roughly an order of magnitude. In contrast, the star formation histories of the Milky Way and nearby galaxies of similar masses appear to have declined much more slowly (e.g., Panter et al. 2007; Fraternali & Tomassetti 2012). Supernova-driven accretion provides an explanation for this apparent contradiction, as the presence of an active star-forming disk allows the Galaxy to continuously cool and collect fresh gas from its corona at significant distance from the center despite episodic re-heating by Sgr A*. We speculate that supernova-driven gas accretion has been the way in which the cosmological hot-mode accretion has fed the star formation in the Milky Way and similar disk galaxies after the initial cold-mode phase. The ability of the MFB12 model to account so nicely for the *HST* absorption-line data suggests that this picture is correct.

The same mechanism also explains the dichotomy between the SFRs of blue-cloud and red-sequence galaxies of similar masses. If star formation were sustained by spontaneous cooling of cosmological coronae, it would be difficult to understand why galaxies residing in similar potential wells—and therefore realistically surrounded by similar coronae (Crain et al. 2010)—can have completely different current SFRs. The puzzle remains even if star formation were fed by the tail of the cold-mode accretion as suggested by Fernández et al. (2012) among others. By contrast, in our scheme it all comes down to the presence or absence of a (star-forming) disk of cold gas. The disk effectively acts as a *refrigerator* that cools and carves out the corona from below. As long as a galaxy is able to retain its gaseous disk it can hope to harvest more cold material from the corona, but when the disk is gone it becomes irreversibly "red and dead."

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